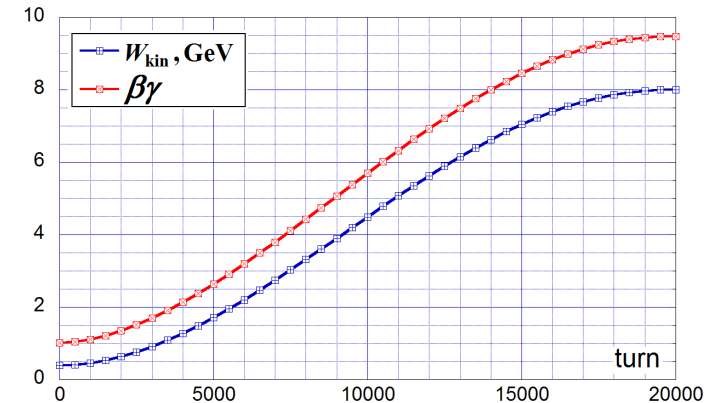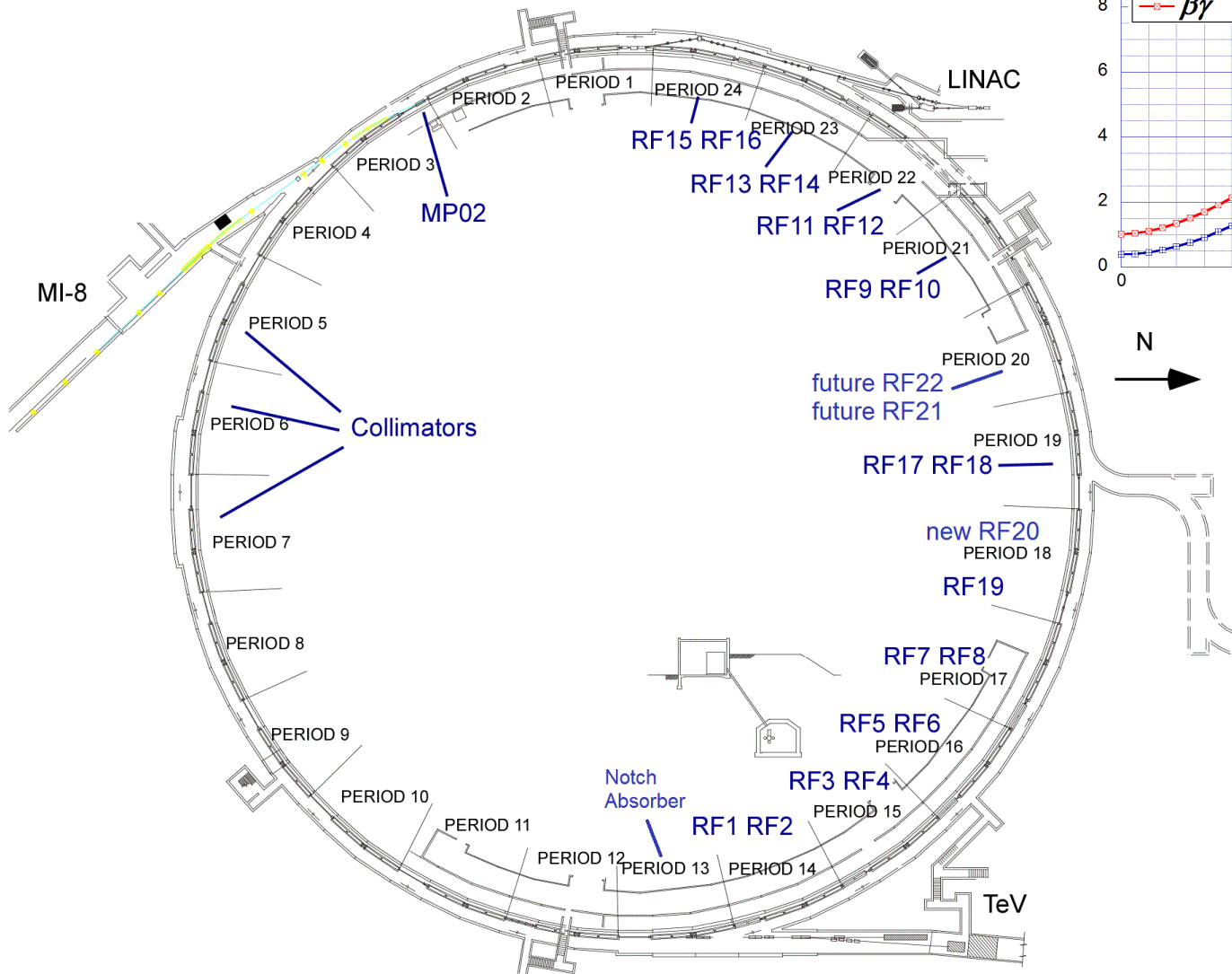# Booster Collimation Upgrade Plans

Valery Kapin

PIP-I+ Booster collimator and Shielding Assessment
15 November 2017

Relevant reports & talks

1) V.Kapin et al, "Study of Two-Stage Collimation System in Fermilab Booster", June 12, 2017, Beams-Docs-5519-v1 (The final **write up** for study of existing 2SC in Boo)

2) V.Kapin, "A proposal for **upgrade** of Booster collimation system", PIP meeting 22-Feb-2017, Beams-doc-5340-v1

3) V.Kapin et al., "Collimation in Booster: **Experimental** Results for Horizontal Plane", PIP Meeting, April 19, 2017, Beams-doc-5371-v1

4) V.Kapin, "Booster Collimation: 2-stage vs 1-stage", PIP meeting 24-Aug-2016, Beams-doc-5222-v2 (incl. Exp. Results for **Vertical** Plane)

5) V.V.Kapin et al, "Numerical Simulations of Collimation Efficiency for Beam Collimation System in the Fermilab Booster", NAPAC-2016, Chicago, paper WEPOA20. (approach for collimation **efficiency simulation**)

6) V.Kapin et al "Experimental Studies of Beam Collimation System in the Fermilab Booster", NAPAC-16, paper WEPOA18 (incl. Exp. Results for **Vertical** Plane)

Co-authors: S.J.Chaurize[1,3,6], V.A. Lebedev[1,5], N.M. Mokhov[1,5,6], W.A.Pellico[1,6], T.M. Sullivan[1,3,6], S.I.Striganov[1,5], R.J.Tesarek[1,3,6], A.K.Triplett[1,3,6], I.S.Tropin[1,5]
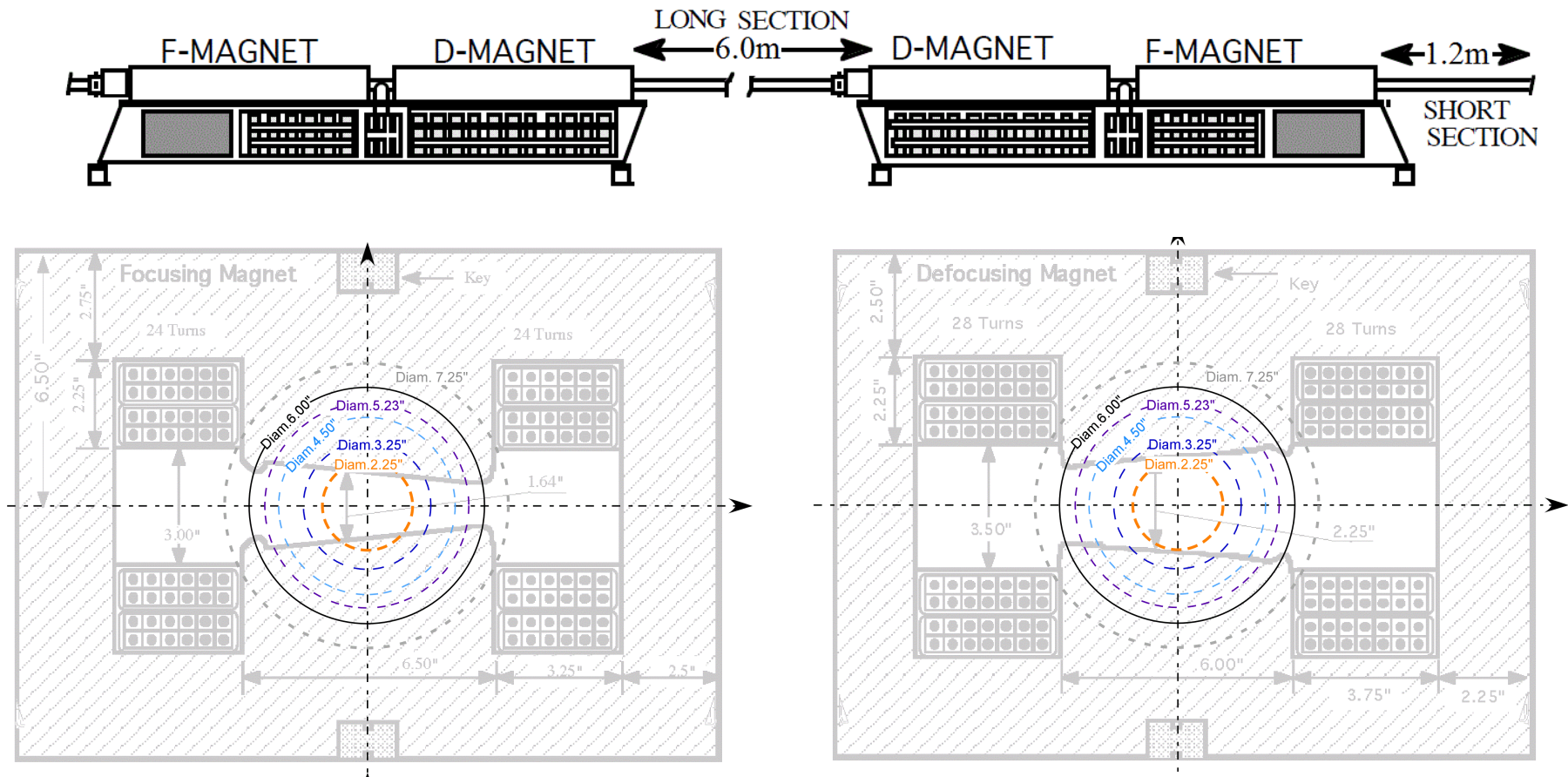
Booster Layout

LINAC

RF15 RF16

RF13 RF14

RF11 RF12

RF9 RF10

PERIOD 1
PERIOD 2
PERIOD 24
PERIOD 23
PERIOD 22
PERIOD 21
PERIOD 20
PERIOD 19
PERIOD 18
PERIOD 17
PERIOD 16
PERIOD 15
PERIOD 14
PERIOD 13
PERIOD 12
PERIOD 11
PERIOD 10
PERIOD 9
PERIOD 8
PERIOD 7
PERIOD 6
PERIOD 5
PERIOD 4
PERIOD 3

MP02

Collimators

MI-8

future RF22
future RF21

RF17 RF18

new RF20

RF19

RF7 RF8

RF5 RF6

RF3 RF4

RF1 RF2

Notch
Absorber

TeV

N

400MeV -> 8GeV
33ms (20,000 turns)

24periods (L=19.8m)
S=474.2m

Plot legend: W_{kin}, GeV (blue), $\beta\gamma$ (red); x-axis: turn (0 to 20000); y-axis: 0 to 10

3

Booster Lattice & Apertures

a) RF-cavities (Diam. 2.25"); b) regular beam pipes (Diam. 3.25");
c) corrector package (Diam. 4.5");
d) special aperture in S12 (Diam. 5.23" shifted horizontally by 2 cm outwards);
e) 0.5 meter pipes between F and D magnets (Diam. 6.00");
f) flanges of combined-function magnets (Diam. 7.25").

4

Aperture restrictions

| element	β_{hor} / β_{ver}, m	σ_{rms}, mm	$3\sigma_{rms}$, mm	sizes of "good field" area		
				$2a$ / $2b$, inch	a_h / b_v, mm	a_{min} / b_{min}, in σ_{rms}
F magnet	33.75 / 10.82	8.2 / 4.6	24.6 / 14.0	4.3"×1.64"	54.6 / 20.8	6.6 / 4.5
D magnet	17.30 / 20.47	5.9 / 6.4	17.6 / 19.2	3.0"×2.25"	38.1 / 28.6	6.5 / 4.5
Long (RF-cavity)	7.59 / 20.47	3.9 / 6.4	11.7 / 19.2	Diam. 2.25"	28.6 / 28.6	7.3 / 4.5

The minimal **vertical** apertures $a_{min}=4.5\sigma_{rms}$ at 3 locations of each Booster periods:
1) junctions of F magnets with 0.5 m short drift sections between F and D magnets;
2) junctions of D magnets with the long straight sections; 3) at drift-tubes of RF-stations.

The minimal **horizontal** (physical) apertures $a_{min}>6.5\sigma_{rms}$ are quite large

Computed gradients at injection & extraction (R.Bilinge, PAC-69, p.969) =>
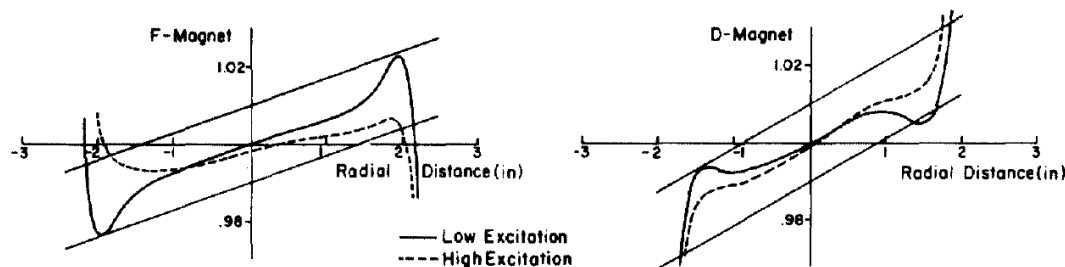
Measured & design gradients at injection (E.Gray, 1976, TM-695A) =>
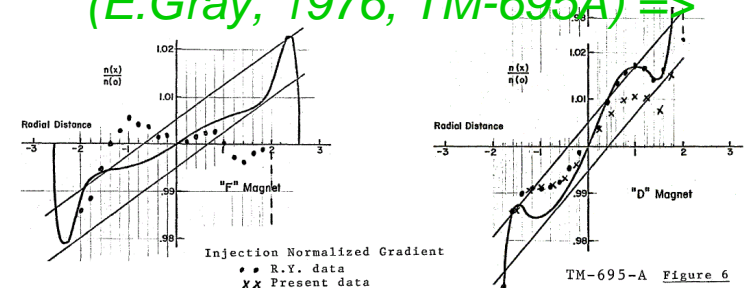
There are "not-well-known" non-linear gradients even within "a good field"=>
Non-linear beam dynamics (non-linear trajectories)

5

Apertures & 2004 design of 2SC

A.Drozhdin et al., "Commissioning of Beam Collimation System at Booster", Beams-doc1223-v1 (2004): "Beam size is defined by the position of primary collimator …located at $3\sigma_{x,y}$ of the beam. … $3\sigma_{x,y}$ – beam envelope."

A.Drozhdin et al., "Booster Beam Loss at Injection" (2011, unpublished), slide 3 :
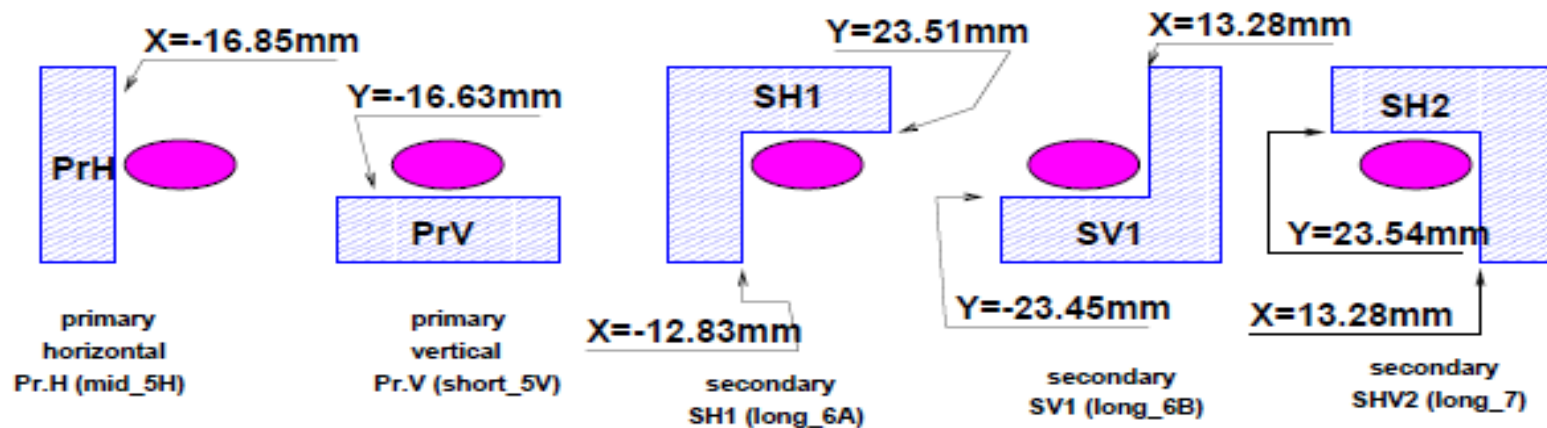
Horizontal and vertical position of collimators. Design of June 2004. Primary collimators are at $3\sigma_{x,y}$, secondary collimators are at $3\sigma_{x,y}+2mm$.

2011 design optimizations of 2SC

A.Drozhdin et al., "Comments on existing collimation system performance", pp.34-37 in Beams-doc4029-v2 "Proposal for Booster notching improvement" (2011):
*"Conclusions: Put secondary collimators at 3.5σ-4σ in both directions, and use primary collimators located at 1mm-2mm close w/r to secondary ones.
… recommended position with collimators 3.85σ$_{x,y}$ (bottom)."*
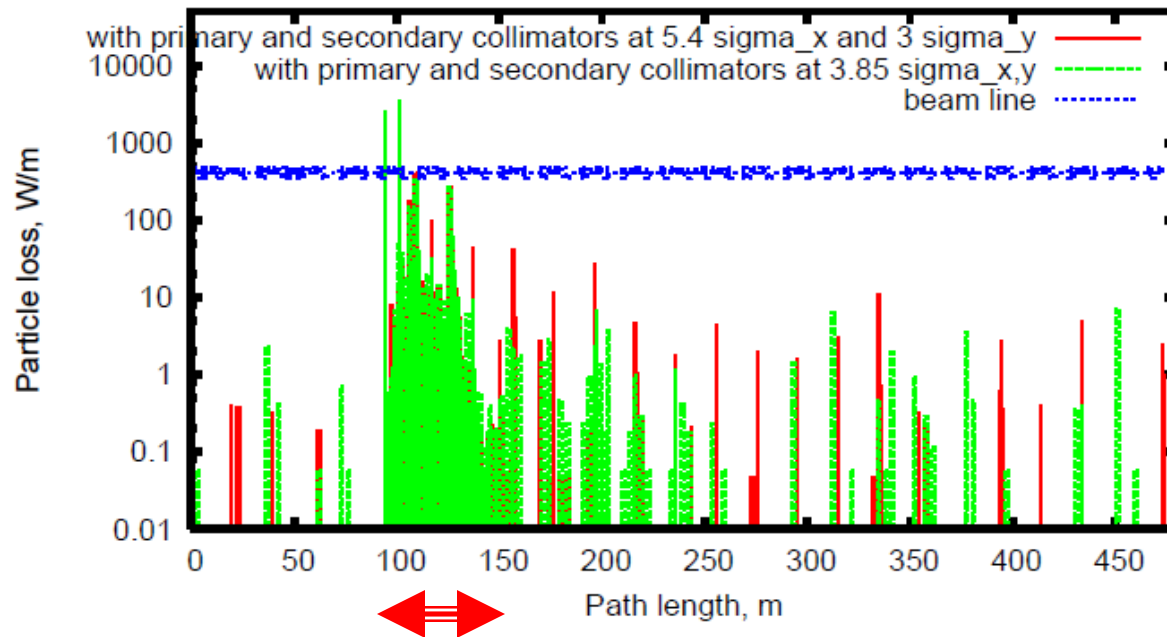
VK-comment:
1) no essential difference between red & green bars;
2) Loss spread over ~30÷50m (total length of sec. colls ~4m)

Loss distributions of halo protons in accelerator with primary and secondary collimators locatedat **5.4σ$_x$ /3σ$_y$** and **3.85σ$_{x,y}$.**

5.4σ$_x$ is very close to Booster aperture restriction, that affects *big losses around the ring*.

Reasons for a Low Efficiency of 2SC

[3.4.1.4 in ref.1]

1) **Small apertures** of gradient magnets and RF-cavities do not allow a usage a rather thick foil (e.g. 400 μm Cu >60% lost on apertures).

A forced solution: usage of thinner foil

However, portion of escaped protons (through 2mm gap) is in a range from 50% for 50 μm Cu foil till 90% for 10μm.
Escaped protons are out of control (*Uncontrollable multi-turn losses*) and have a small impact parameter => out-scattering effect is not reduced and should be almost the same as for 1SC.

Then, optimal 50 μm Cu foil with collimation efficiency ~50%, which is close to a single stage collimation.

2) Non-optimal phase locations of the secondary collimators.
It be compensated after many turns (is it a Booster case ?)

3) Variable 3σ-trajectories sitting on c.o in Booster (time-variable parameters, mismatching, not measured&controlled at all !).

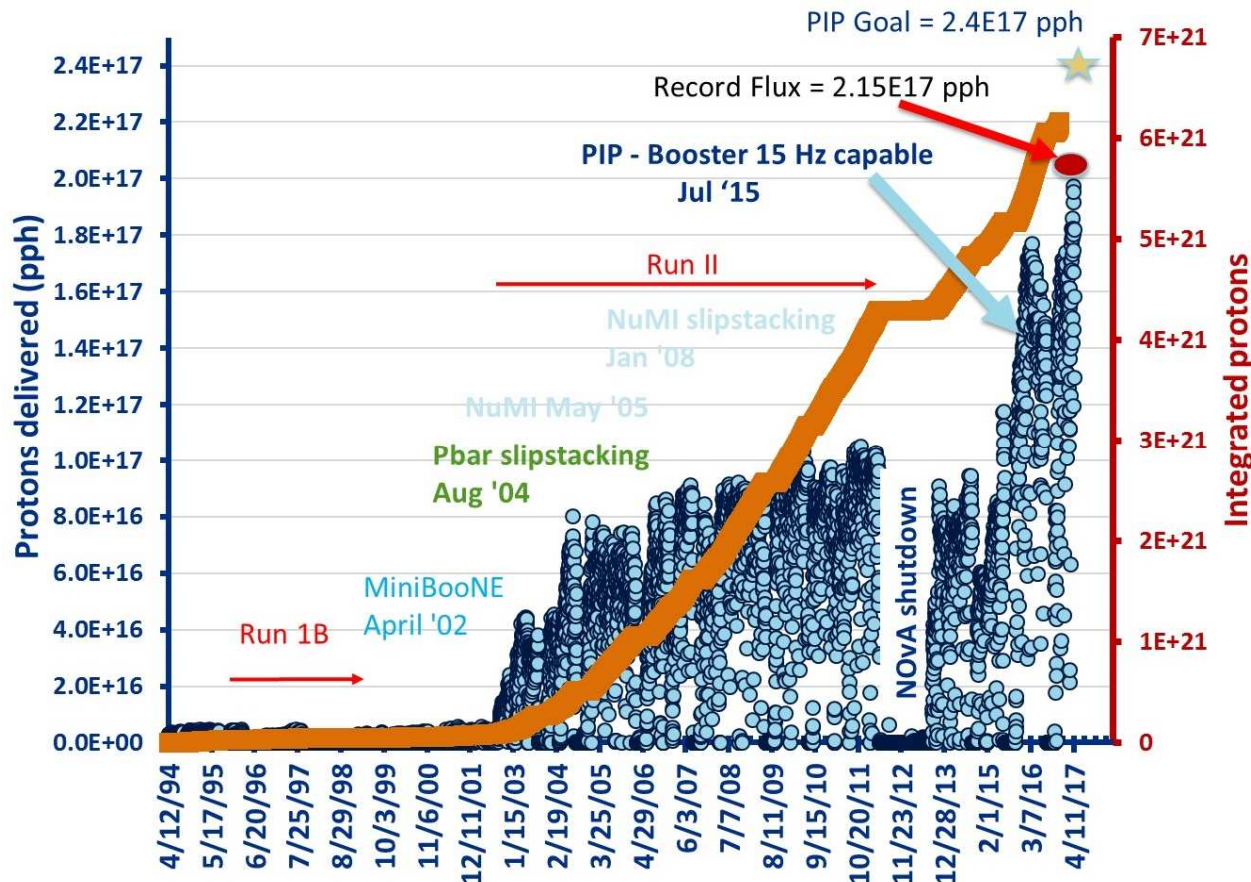4) Experimental beam studies did not show any advantages of 2SC in comparison to 1SC.

Evolution of Booster proton delivery

(SN, 04/18/17): PIP campaign is $2.4 \cdot 10^{17}$ protons per hour while maintaining 2012 activation levels, ensuring viable operation of the proton source through 2025. PIP-II with the new SC linac (~2023) requires up to $4.7 \cdot 10^{17}$ pph in Booster.

To prepare Fermilab accelerator complex to PIP-II requirements, a new flexible campaign named as PIP-I+ with a goal $2.7 \cdot 10^{17}$ pph (?) is proposed as follow-on to PIP.

PIP Goal = 2.4E17 pph

Record Flux = 2.15E17 pph

PIP - Booster 15 Hz capable
Jul '15

Run II

NuMI slipstacking
Jan '08

NuMI May '05

Pbar slipstacking
Aug '04

MiniBooNE
April '02

Run 1B

NOvA shutdown

Protons delivered (pph)

Integrated protons

~2004 commissioning of Present collimation system => ~ $2.0 \cdot 10^{16}$ pph
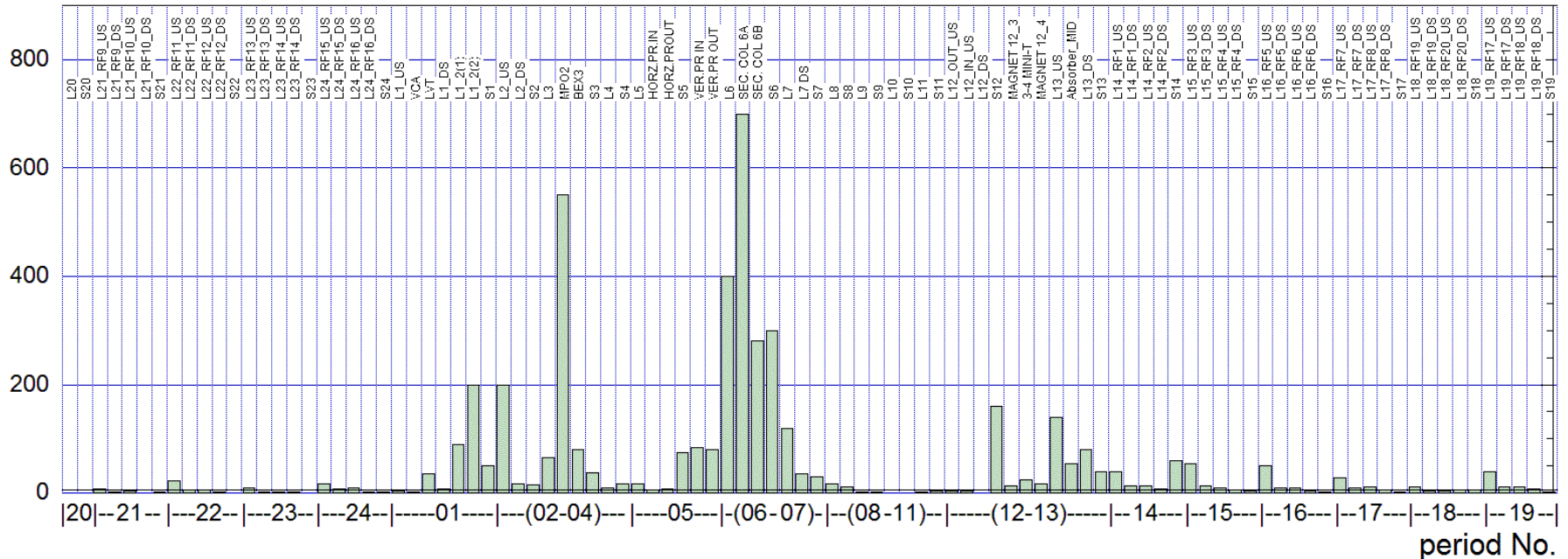
Increase in Booster intensity :
PIP (2017)   ~x12
PIP1+   -> ~x14
PIP-II   -> ~x24

More effective control of beam losses via improved beam efficiency & collimation

9

1-foot Residual Radiation Data (03/31/2017)

Avg via (B87@8h-before): up-time=95.8%; 12ev/sec; $3.8 \cdot 10^{12}$ppc; $1.7 \cdot 10^{17}$pph; Eff=91%

High radiation levels in the following regions (see Boo layout slide #3):
1) Injection - period 01 (up to 200 mrem/hour);
2) Extraction – around period 3 (up to 550 mrem/hour);
3) Collimation – periods 5-7 (up to 700 mrem/hour)
4) Notching – periods 12 & 13 (up to 150 mrem/hour)

Relatively small radiation in "RF" periods 14-24 (< 200 mrem/hour), however
RF stations require a frequent maintenance works -> exposure of rad. workers

Res. Radiation in "RF" periods (03/31/2017)

RF station: 2gaps with drift-tubes (i.d.=2.25"); L14-24 (except L20) with pair RF stations
Each period 5-point meas.:
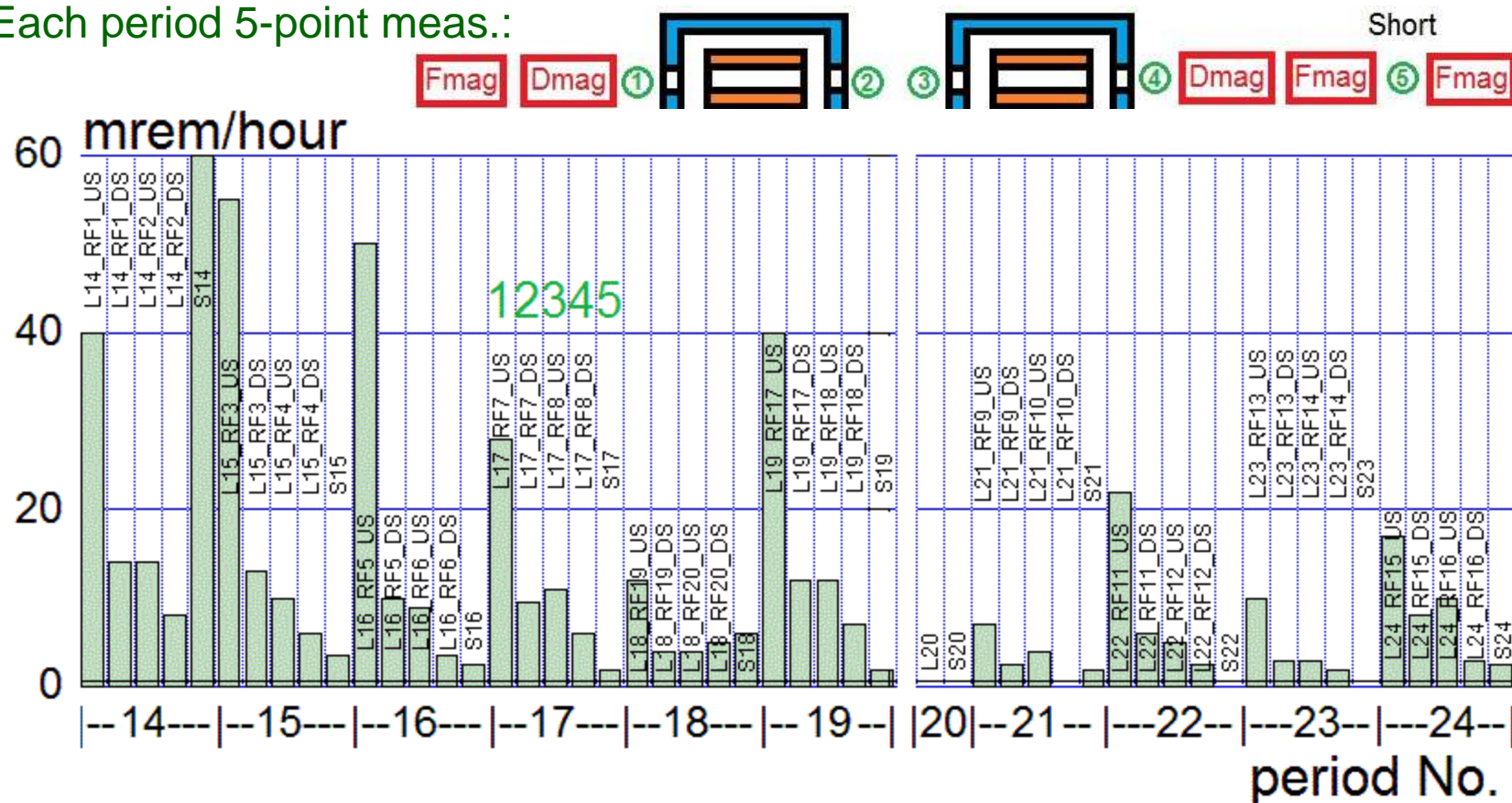
1) Within Longs: the highest radiation exists at points #1 (UpS of 1st RF station),
   then it monotonically drops vs the point number (1,2,3, and 4);
2) Shorts (#5): minimal radiation over period, except of periods 14 & 18;
3) There 3 sequent regions where average level of residual radiation drops
monotonically: 1st region - 14÷18; 2nd region - 19÷21; 3rd region - 22÷23.

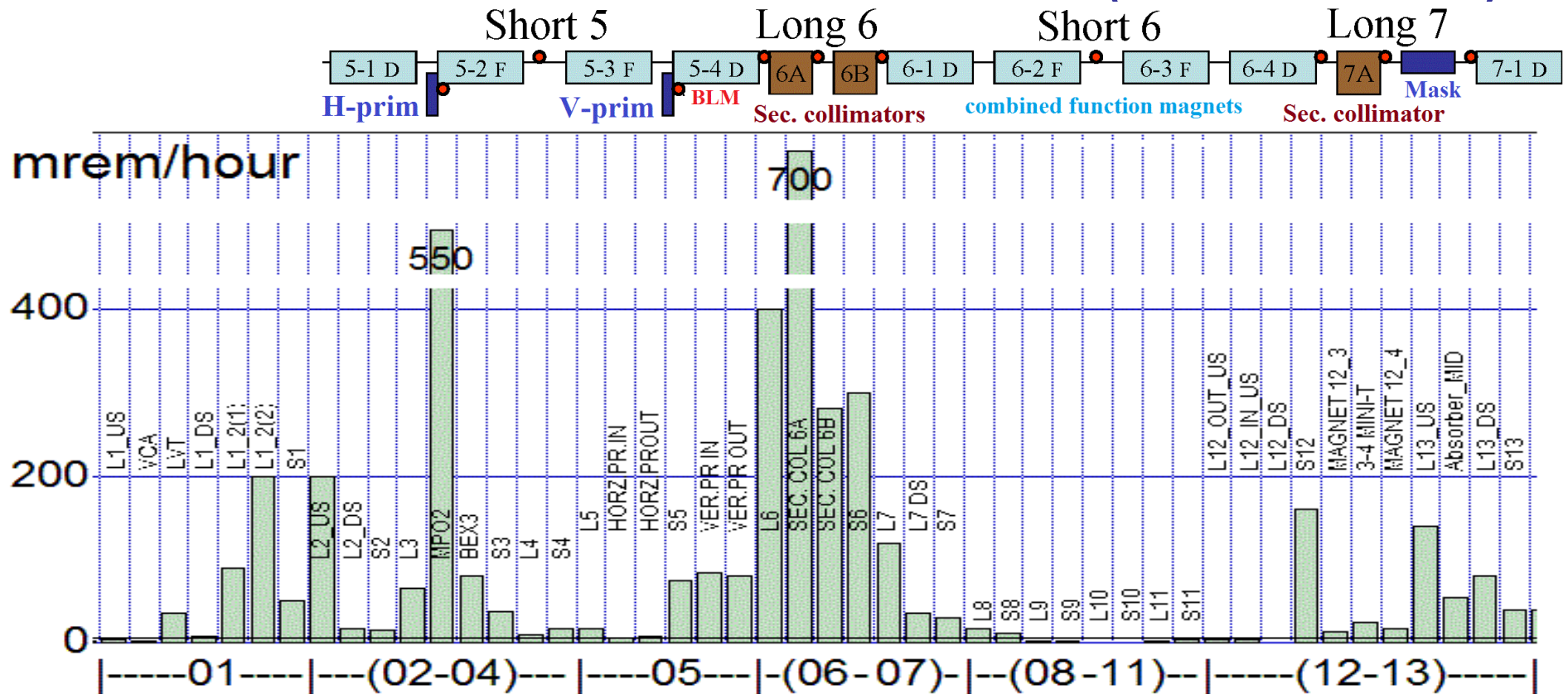# Comments on Res. Radiation in "RF" region

The above plot suggests:

❖ every pair of **RF stations** acts as **a sequence of aperture restrictions** for incoming beam (if $r_{trajectory} > a_{RF-DT}$).

❖ note, this happen in presence of **acting collimation system**.

❖ => a considerable part of the **beam halo avoids** the apertures of collimators and directly hit apertures of RF stations.

❖ That is the **RF stations** act in part as **a supplementary collimators** providing a relatively high radiation in their vicinity.

RF stations require frequent, complicated & long maintenance procedures;
⇒ **the reduction of residual activation near RF-stations is very desirable**
(to avoid excessive radiation exposure of maintenance workers).

This circumference can also drive the **need for an upgrade of existing collimation system** or even for designing and building a new one.

Details of 1-foot Res. Rad. Data (03/31/2017)

Short 5 | Long 6 | Short 6 | Long 7

| 5-1 D | 5-2 F | 5-3 F | 5-4 D | 6A | 6B | 6-1 D | 6-2 F | 6-3 F | 6-4 D | 7A | Mask | 7-1 D |

H-prim **V-prim** **BLM** **Sec. collimators** **combined function magnets** **Sec. collimator**

mrem/hour

700

550

400

L1_US, VCA, LvT, L1_DS, L1_2(1), L1_2(2), S1, L2_US, L2_DS, S2, L3, MPO2, BEX3, S3, L4, S4, L5, HORZ.PR.IN, HORZ.PR.OUT, S5, VER.PR.IN, VER.PR.OUT, L6, SEC.COL 6A, SEC.COL 6B, S6, L7, L7.DS, S7, L8, S8, L9, S9, L10, S10, L11, S11, L12_OUT_US, L12_IN_US, L12_DS, S12, MAGNET 12_3, 3-4 MINI-T, MAGNET 12_4, L13_US, Absorber_MID, L13_DS, S13

200

0

|----01----|---(02-04)---|----05---|-(06-07)-|--(08-11)--|-----(12-13)-----|

Highest in Collimation region: 1) "SEC.COL 6A" (->700 mrem/h) between abs. 6A & 6B;
2) "L6" (~400mrem/h) at front of 6A; 3) "SEC.COL 6B" (~300mrem/h) behind of 6B;
4) "S6" (~300mrem/h) at short S06; 5) "L7" (~100mrem/h) at front of 7A
Relatively small (<50mrem/h) at primary (unused) and DS of absorber 7A

A)"Boo never lost grad.magnets due to foil failure, but it may happen first here"!
B) Fermilab individ. job stop limit ~55mrem => rad. worker <5min!!! (700/60x5=58)
No immediate access of collimators => long cool-off times => high Boo down times

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Present Collimators in L06-L07
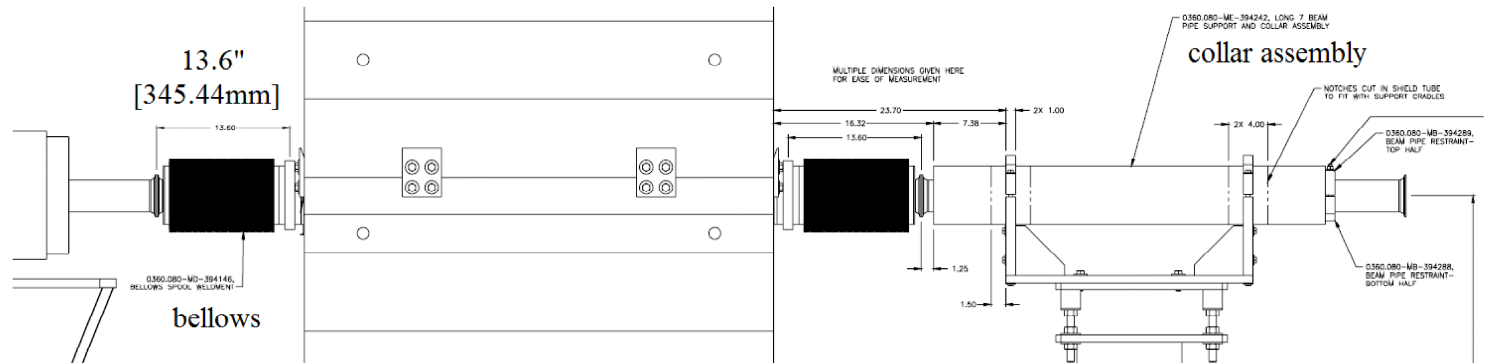
Design by "Bartoszek Eng.": integration of collimator jaws & shielding steel (10.6ton); both move horiz. & vertically by ±1.50", yaw & pitch rotations by ± 10 radians.
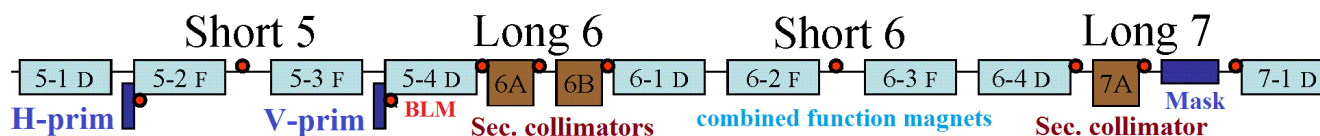**3 identical** absorbers 6A, 6B, and 7A
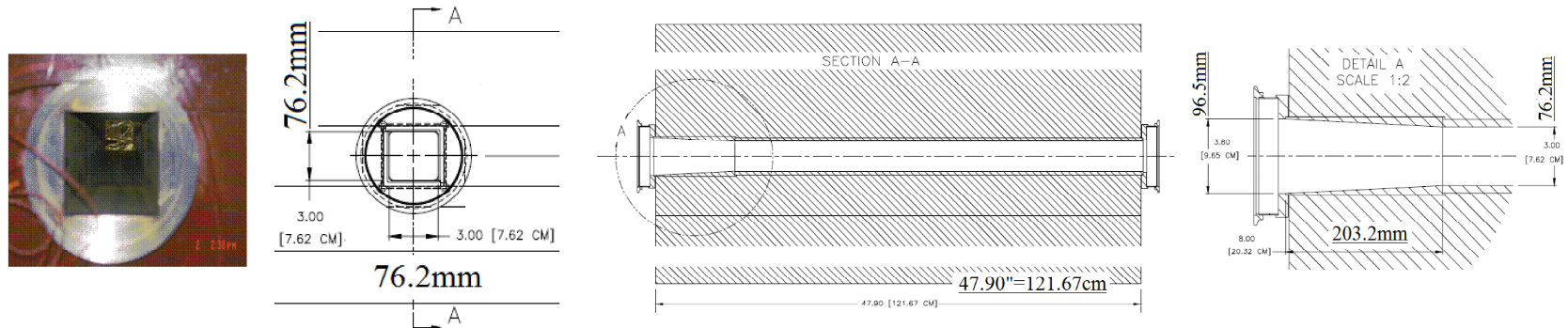
Jaws: the 1.22m long vacuum liner with square 3"x3" cross-section; only upstream end is tapered by 2cm (hor&vert).
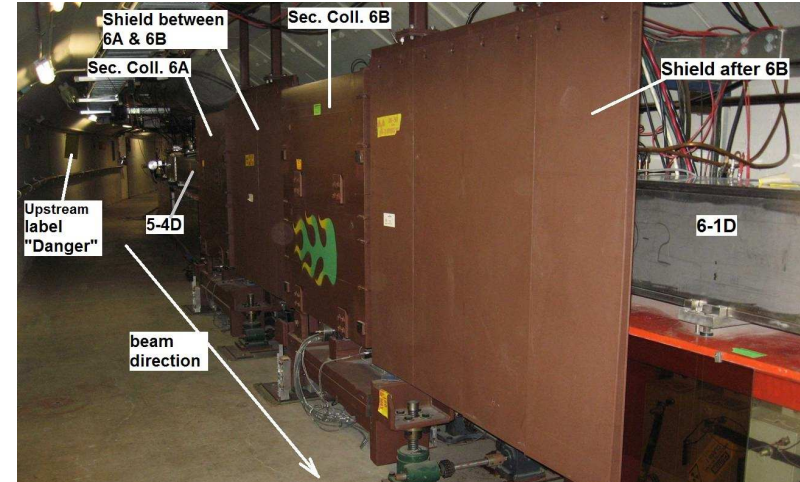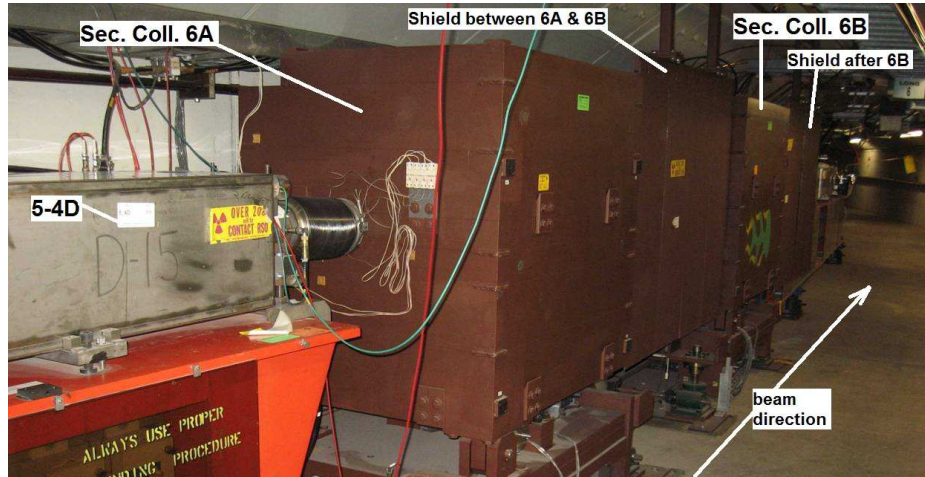
Bellows:
a total laterel offset up to 2.12"

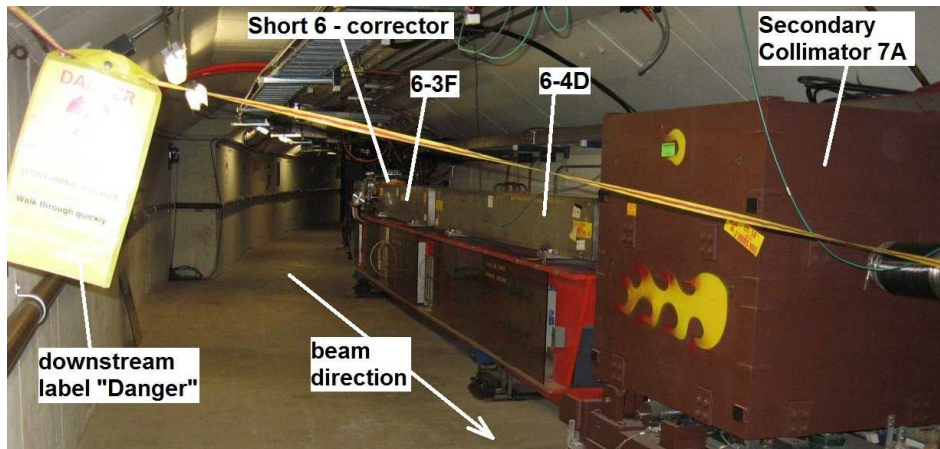Shielding (up to 8GeV): only transverse shielding; input/output bellows w/o any shielding

Photos of Present Sec.Collimators

"L6" (~400mrem/h) at front of 6A; "SEC.COL 6A" (->700 mrem/h) between abs. 6A & 6B

"SEC.COL 6B" (~300mrem/h) behind of 6B

Except of absorbers, there is no any shielding for other Booster elements including primary collimators.
2 supplementary shielding assemblies (steel plates hanged up on hooks):
1) between 6A & 6B; 2) behind 6B

"S6" (~300mrem/h); "L7" front of 7A (~100mrem/h)

"Contamination area: S05 ÷ ds of 7A" (~30m)

15
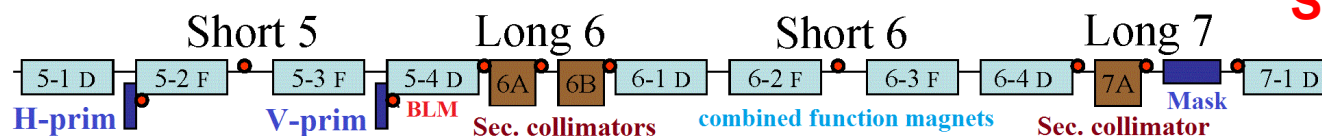
Comments on Existing Collimators

Plot (2004) shows a relative %-change in activation since collimators (1SC) operated:
1) **reduced activation** by 40÷50 % around much of the ring, particularly in **RF region**.
2) **increased activation** of ~ 50% in injection region (period 1) and of 50 ÷ 250 % in the **collimators regions** and immediately downstream (periods 6, 7, 8).

E.Prebys, "Booster Status", July 8,2004 talk
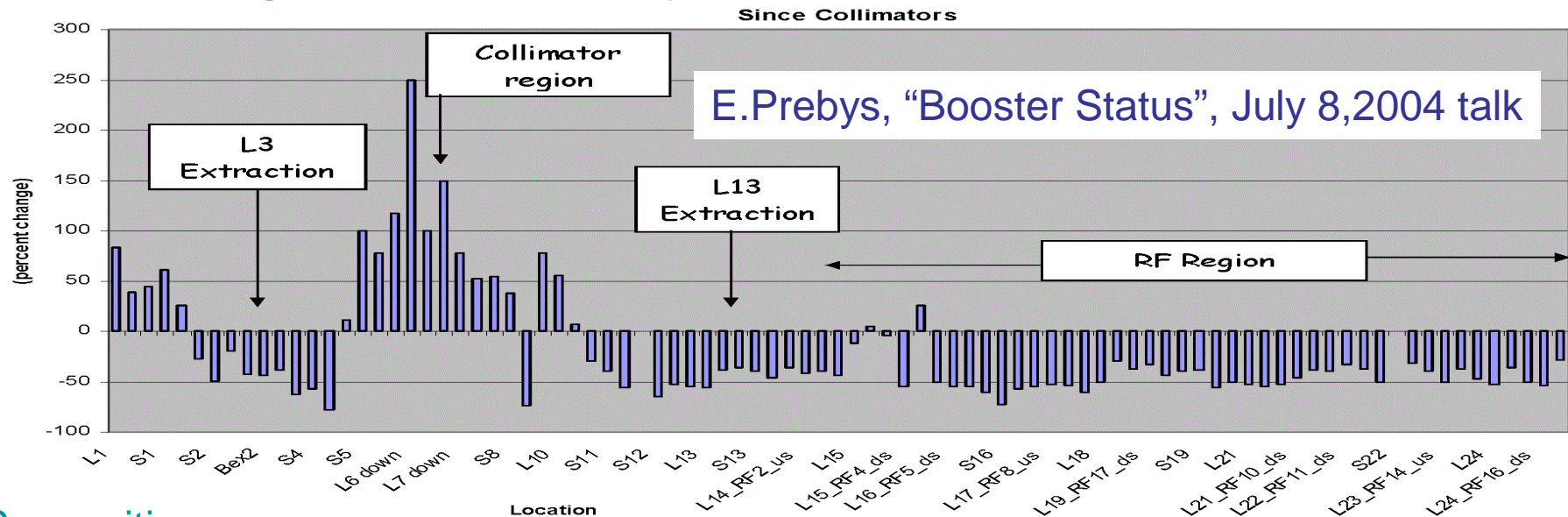
Supposition:
1) High radiation at collimators is mainly due to out-scattered protons at 1SC regime
2) a considerable part of the halo avoids the collimator apertures and directly hits apertures of RF stations due to a short phase length occupied by collimators.

Idealized cure prescriptions:
    for "1" – effective capturing out-scattered protons inside collimator block (a'la 2SC)
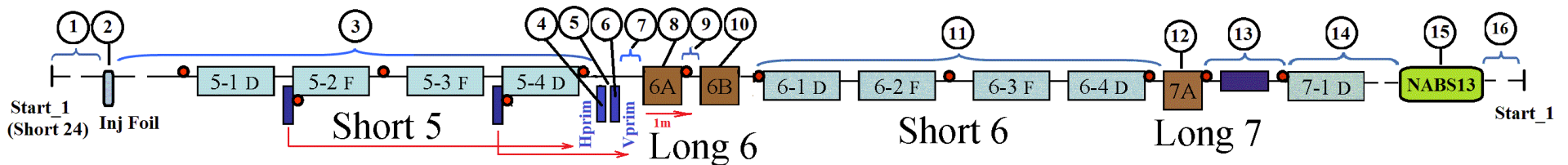   for "2" – extend phase length of collimation are via usage of multiple collimation units

Layout of simulated 2SC with "thick" foil

Existing models of the sec. collimators in L06 & L07 are used for simulations of new 2SC with "thick" primary foils located at the beginning of L06.
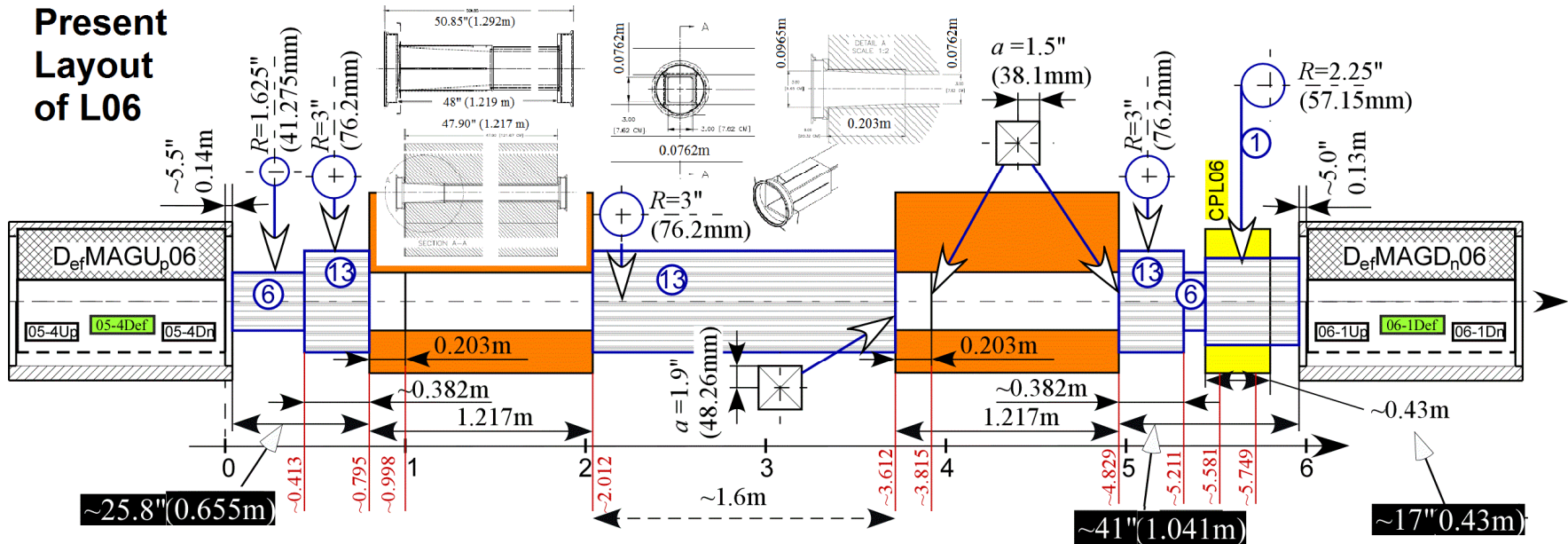

Layout of the new 2SC system used in simulation: a) Set Prim. colls at front of 6A;
b) shift of 6A by 1m;

Notice. New system could be installed in a free long section of periods 8,9,10, while old are kept w/o changes

Simulations (MADX+MARS): 2SC with "thick" foil

1) Existing hardware W/O shielding of 4÷7,9. => ε_{halo}=75% in one pass vs (t_{Cu}=4mm). It is the same as the 2004 2SC design after 100 turns (ideal optics during 100turns)
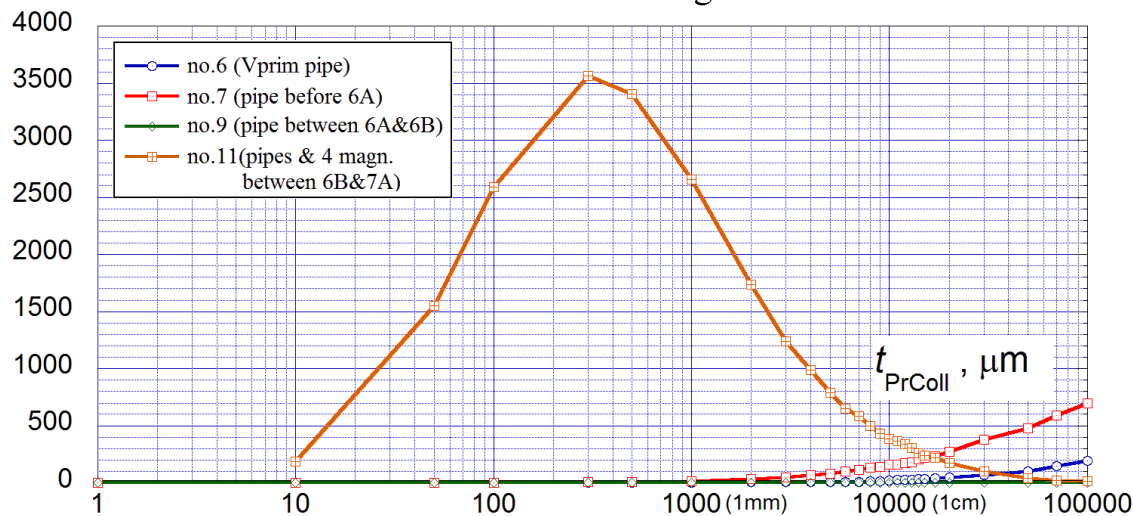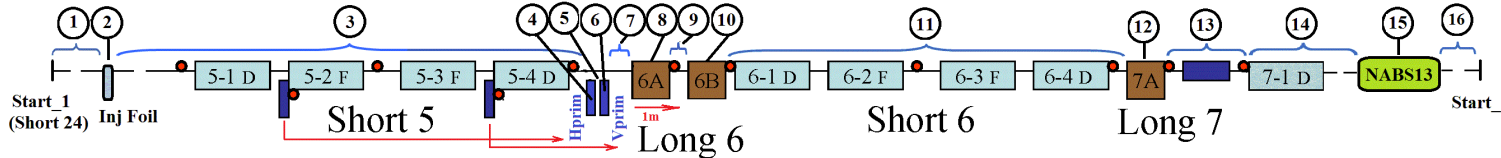

2) If we "imaginary shield" 4÷7,9 (beam pipes & Prim. Colls) => Losses on 4÷7,9 treated as "useful"! Such "shielding" was simulated via enlarged beam pipes (i.d.=1m). Losses vs t_{Cu} shown on the left plot
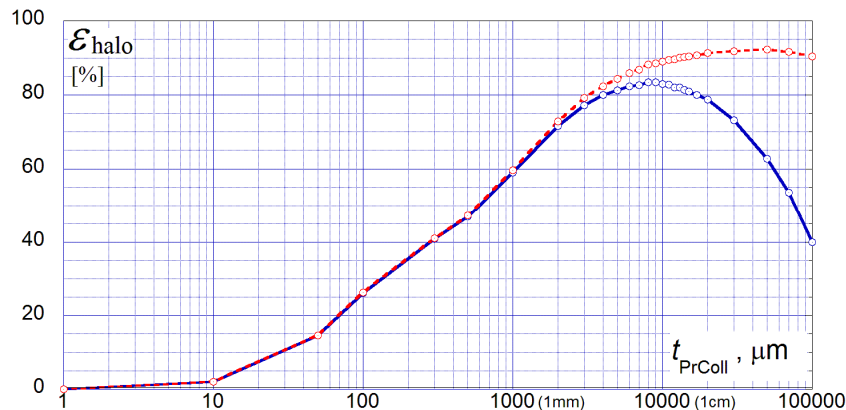
3) Blue-curve: max ε_{halo}=83% if losses on unshielded primary still treated as "bad" ("unshielded" prim.) Optimal t_{Cu}~8mm

Red-curve: max ε_{halo}>90% if primary is shielded ("good" losses) t_{Cu}~1 ÷ 10cm

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Resulting 2SC with "thick" foil
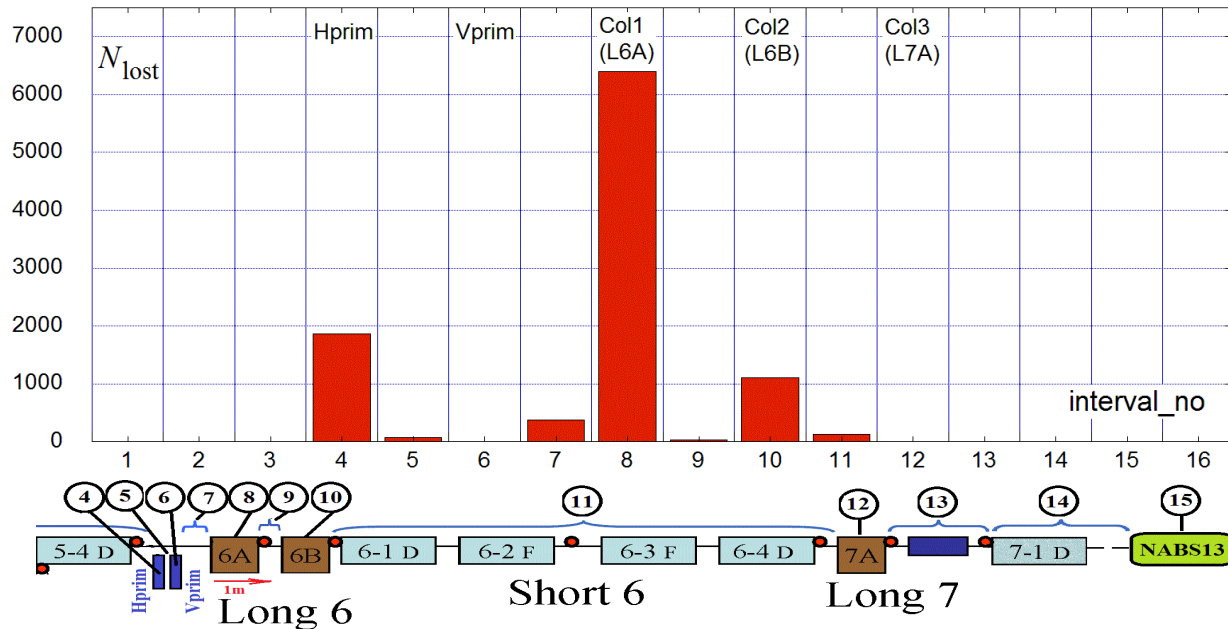
Example of loss distribution
for the new 2SC system
with primary t_{Cu} =3cm
All 4÷7,9 are shielded

Existing 2SC is difficult for Booster (to control a halo position during ~100 turns)

New "thick-foil" 2SC is optically easier: the same efficiency (~75%) in a single pass

Efficiency of new 2SC can > 90%, if beam pipes between sec. colls (& around prim) will be enlarged (and well protected)

With a new 2SC beam losses "ineff~(1-eff)" could be reduced by a factor ~2-3 (from ineff=25% to ineff=8%)

New system (2 prim + 2 sec) can be located in empty long section, e.g. L08, 09, 10.

New 2SC may be duplicated while keeping existing 1SC (probably, a better protection of RF cavities, if halo particles with fast-growth rates are able to avoid a single 2SC)

Realistic design will require simulations with MARS code

~Somewhat similar 2SC at RAL RCS ISIS (SNS)

It is not a classical 2SC as in colliders with (eff~99,xx%, ineff~losses~0.xx1%).
It is just **a local solution** for existing machine with eff~80-90% better than 1SC

70MeV -> 800MeV, C=163m, 3xE13 ppp, 160kW->240kW

Collimation systems are located in one well shielded 5m drift section
(10 movable beam collectors – 3 primary + 7 secondary)
It evolves from 198x till now (~35years; successful ?)

Elevation View of the Collectors in Super-Period 1
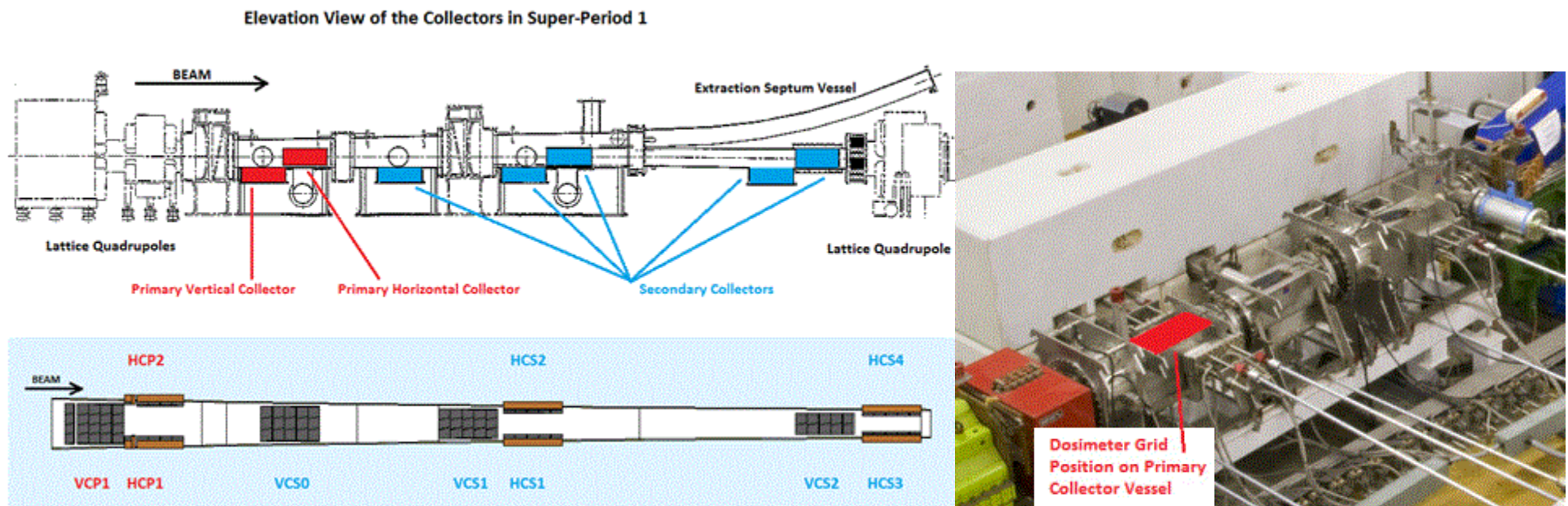
1) PAC-1981 p. 2125, "Features of … SNS synchr": **scrapers** 70-100MeV (Cu+graphite), 800MeV (stainless)
2) EPAC-2004, p1464 "Studies of Beam Loss Control … ISIS"
3) IPAC-2014, p893 "Activation model of ISIS Collectors", 10collectors (3prim+7sec. collims) in straight one

Outlook of possible solutions

▪A new collim. unit will consist of **4.2 m long** well-shielded vacuum vessel containing 2 movable primary coll at its upstream end and 2 ~1m-long movable sec. hor. & vertical collim. jaws at its downstream end.

▪The vacuum chamber between primary and secondary collimators on the length of ~1÷1.5m should have a quite large diameter to ensure a free drift of scattered protons from primary to the front edges of the secondary jaws.

▪New coll. unit can be located at some empty long section, e.g. L08 (9,10).

The new 2SC unit may be duplicated, if it will demonstrate good operations. Staged plans could be suggested.

**The 1st stage** - the new unit installed in Long 8. Several questions:

a) if unit could effectively intercept halo as existing 1SC and reduce residual radiation in surrounding area (period 8);

b) if new system operating together with existing absorbers could redistribute beam losses & reduce max. radiation in the collimation area (periods 6,7,8)

c) if new system operating together with existing absorbers could reduce the radiation levels in remote areas like the RF-cavities.

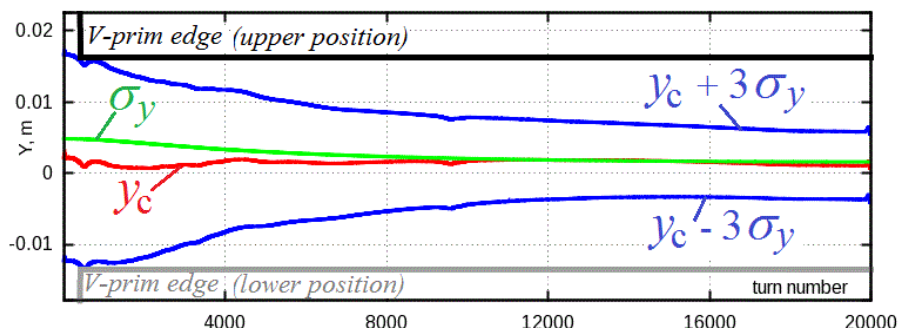**The 2nd stage**, if the 1st stage is successful – duplicate new unit in L09 (& L10)

The 3rd stage, if 1st & 2nd stages are successful – replace 6A&B, &7A by new

Booster orbit & collimation

Vert. beam orbits at S05, ds L06, ds L07
Mean±rms values of 5 pairs meas.
During 2.5 hrs study:
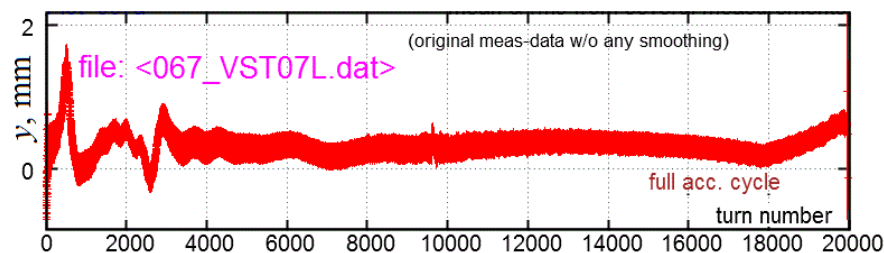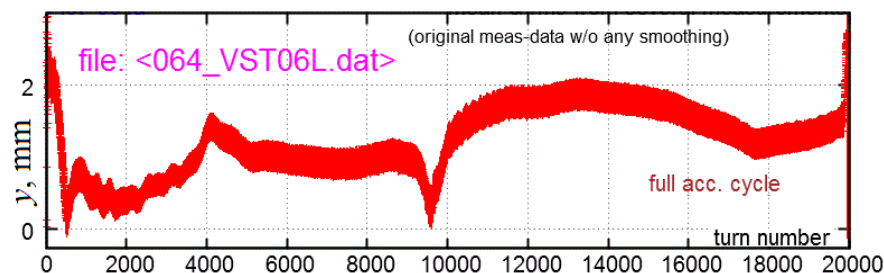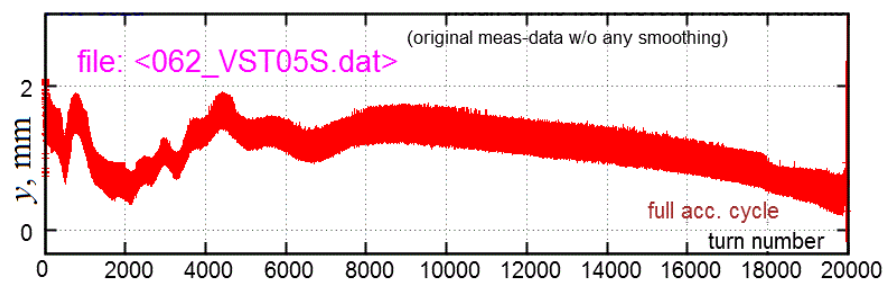
Ideal halo envelopes around real c.o.
for ds 6B:

If collimation from both sides of the beam
feasible (?):
Due to complicated shape of c.o.
the beam could not be collimated from
both sides at the same turn !

Moreover, collimators in different periods
will touch the beam at different turns

=> Difficult to create continual wide-phase
collimation system using the set of several
collimators

Suggested of Plan

Definition: The collimation unit is a 2-stage collimation assembly within a single long section of the Booster. It includes 2 h&v primary & 2 sec. absorbers.

Stage-I: One collimation unit – designed and installed in L08;
Stage-II: if stage-I is succesfull => install the second init in Long-09
Stage-III: if the abobe stages are OK => replace of existing in L06 & L07
with new units

Simulations&Concept. Design - Kapin,Sidorov,Tropin (supervision Mokhov, Pellico):

1. Draft of possible **designs** (Sidorov <- Kapin) => 3D model(s) of collimation unit
2. Simulations with MARS - to **define rad. shielding** (wall thickness) - Mokhov, Tropin
3. Support simplified collimator **MARS model for protons** only - Mokhov, Tropin
4. Simulations **with protons only** (Kapin using the above MARS model #3):
    a) for collimation efficiency of collimation unit (if needed)
    b) protection of far accelerator components (e.g.RF cavities) with several collimators vs rates of emittance growth and difference in "touch-turn"
    c) p-loss distribution around the ring
5. Radiation distribution by MARS from p-loss distributions (Mokhov, Tropin)

1-3, 4a: needed for stage-I; 4&5: needed to prepare Stage-I experiments & next stages
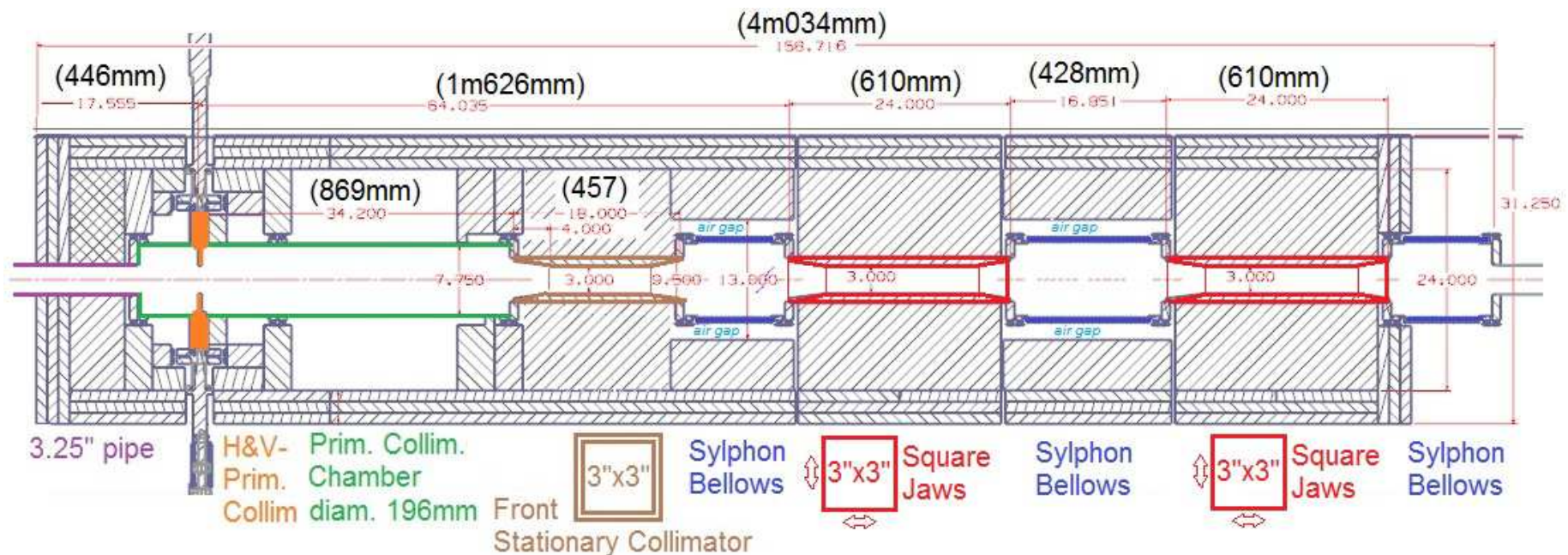
1st Conceptual Design of Collimation Unit

3 designs are considered. Modular structures – 2 parts (part A – similar for all 3 designs):
A) Prim coll. Chamber ended with Stationary collimator; B) sec. collimators assembly

1)"Square Jaws with Sylphons" (Air gaps between sylphon bellows and shielding):
"FrontShield-Pr.Coll-DriftChamber-FixedCollim-

SylBel-HVJaws-SylBel-HVJaws-SylBel"

Implementation of existing design concept with large bellows.

Possible problems – air gaps
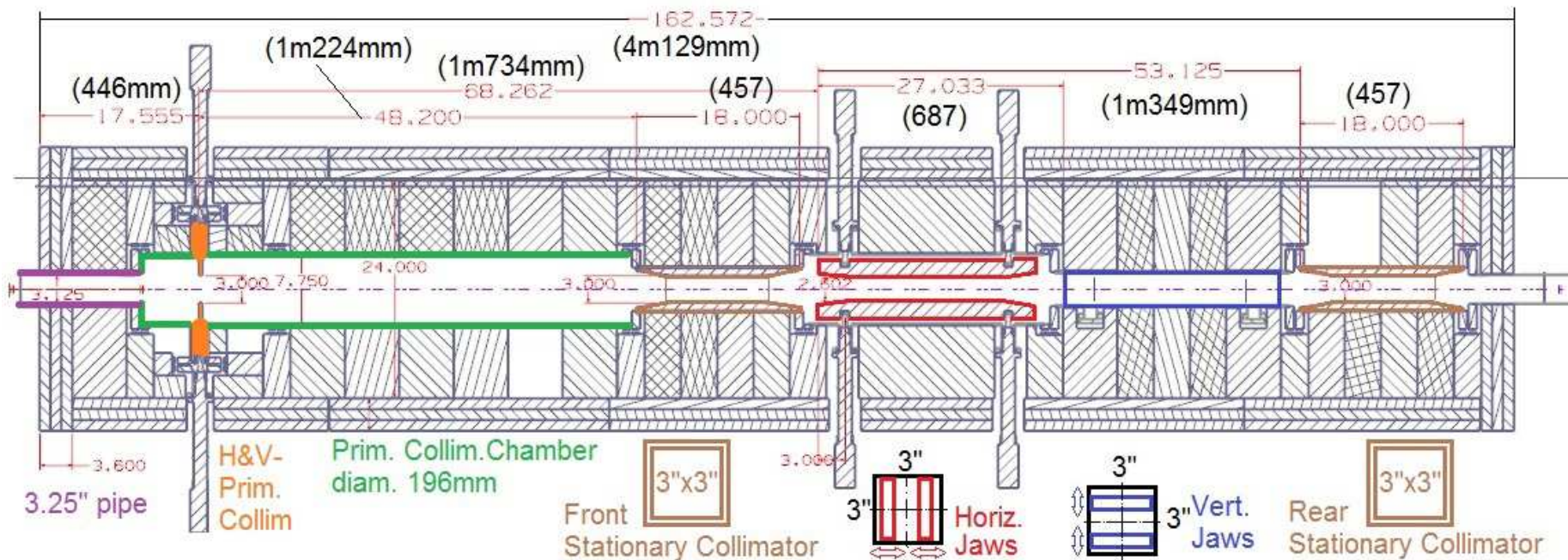(in 2003 L-shape collimators with air-gaps has been canceled)

2nd Conceptual Design of Collimation Unit

2)"Separate H and V Jaws Inserted in Vacuum":
"FrontShield-Pr.Coll-DriftChamber-FrontFixedCollim-
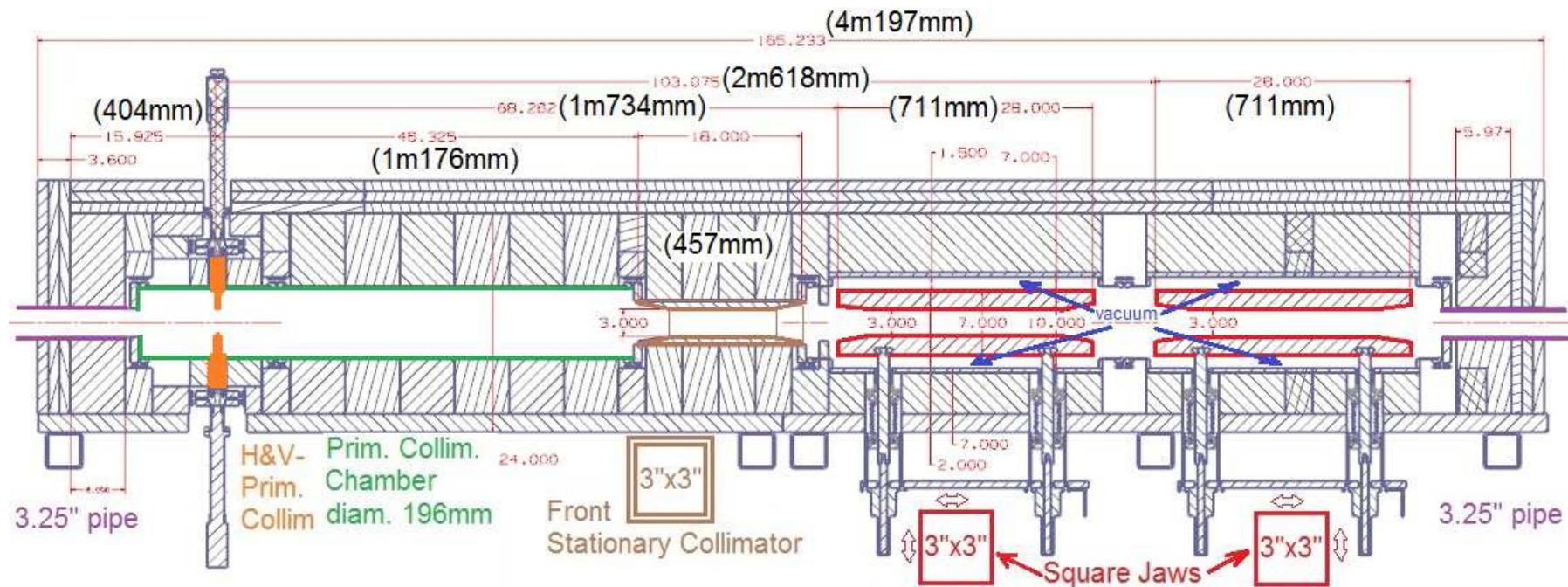HorJaws-VertJaws-RearFixedCollim"

Simplest configuration without air-gaps, but hor jaws are too close to primaries
(increased flux of scattered protons via end aperture – check?)

3rd Conceptual Design of Collimation Unit

1)"Square Jaws (w/o Sylphons) Inserted in Vacuum":
"FrontShield-Pr.Coll-DriftChamber-FixedCollim-
-HVJaws-HVJaws-RearShield"

Most universal close-to ideal implementation with non-trivial motion mechanism
for square jaws inserted in vacuum vessel